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Multiple Harmonic Oscillations in NSTX

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PPPL

and the NSTX Research Team

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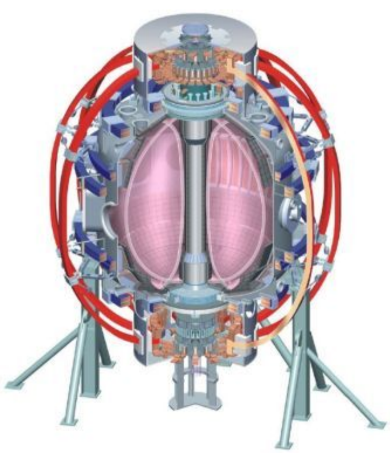

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Outline

NSTX plasmas are rich in MHD

Alfvén eigenmodes: 100kHz – 2 MHz

Kink, tearing & ballooning modes: <100kHz

Resistive wall mode : < 1 kHz

Locked mode: f ➔ 0

Distinct frequency spectrum for MHO:

$f_n \sim n\, \Delta f \sim n\, f_1$

where n = toroidal mode #

1. Island identification in NSTX
2. Multiple harmonic oscillations
3. Effects on transport
4. Relevance to other tokamak experiments

Island in NSTX identified by flat region in $f_\phi(R)$

- *Unlike conventional tokamaks, NSTX has no ECE, and soft X-ray looks at plasma edge.*
- *An island rotates as an entity*

  - characterized by a ***flat region in $f_\phi(R)$ from CHERS***

  (charge-exchange-recombination-spectroscopy – R.E. Bell)
- CHERS data averaged over 7.5 ms – slow response

  For 10 kHz signal, this means averaged over 75 cycles

  ⇔ beware of ***smearing effect***

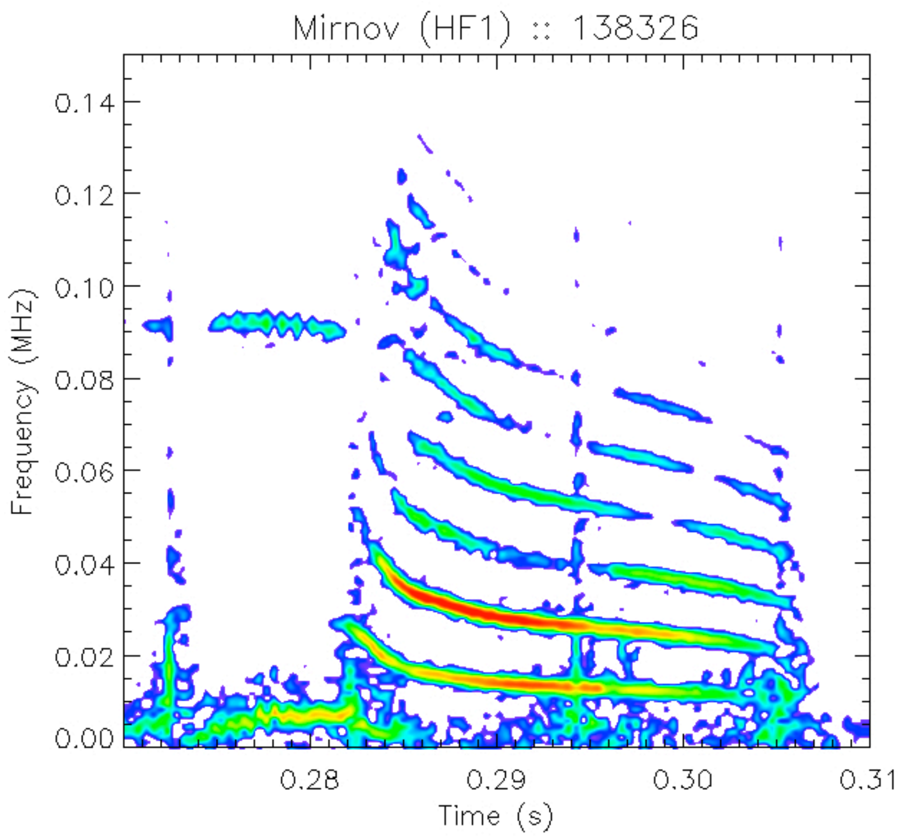
Multiple harmonic oscillation (MHO) is associated with magnetic island

#138326: Ip=0.8MA ELMy H-mode, Pb=2MW, Prf=0.9MW turned on at 0.25s

MHO

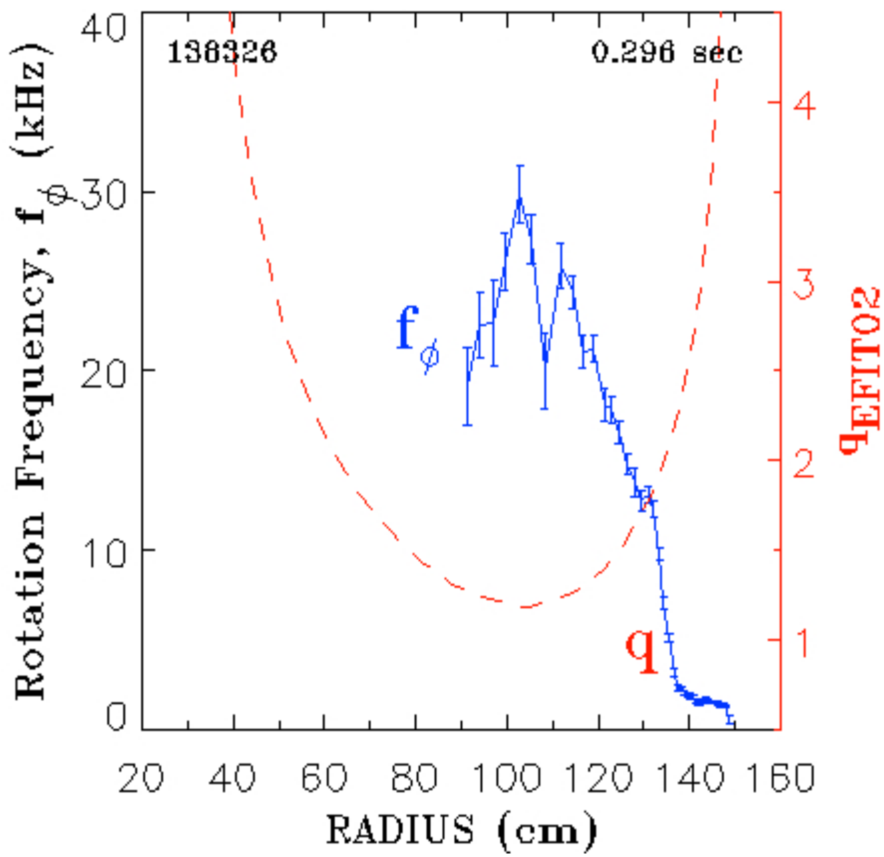
Mirnov signal: $f_n \sim n\,\Delta f \sim n\,f_1$

n = toroidal mode number



At 0.296s, *small island* rotating with $f_\Phi \sim 13$ kHz $\sim \Delta f$

***Smearing effect**: -2.5/+5ms* ⇔ *< 98 cycles >*



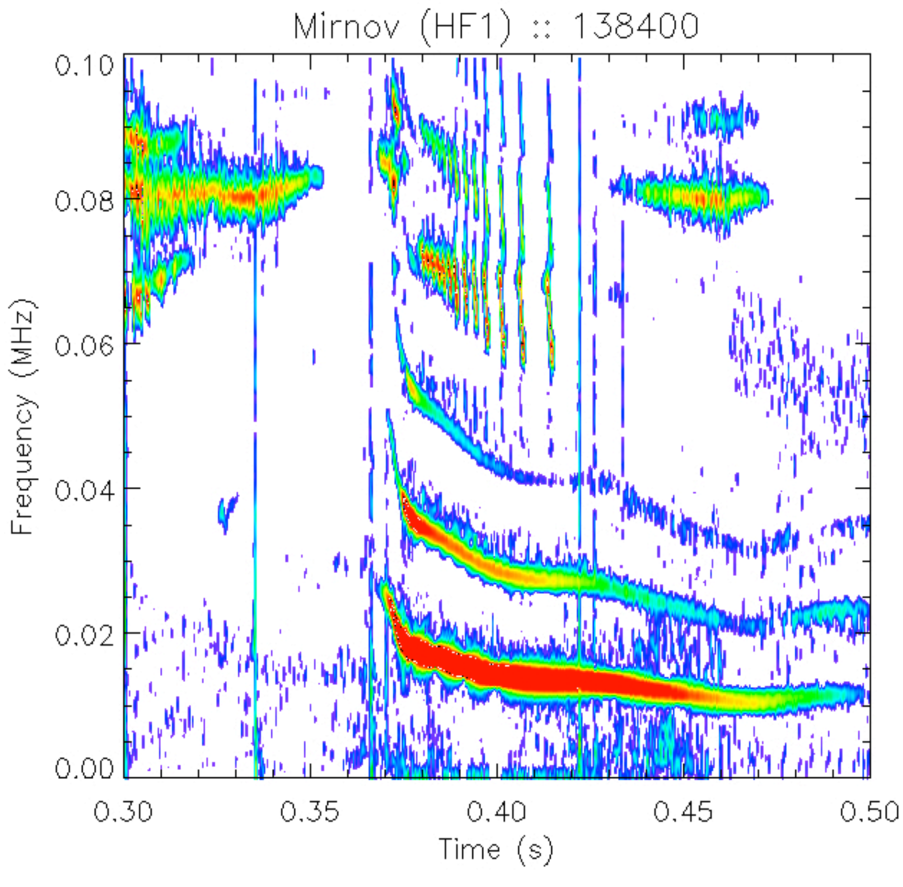
Big island with *high quality CHERS data*

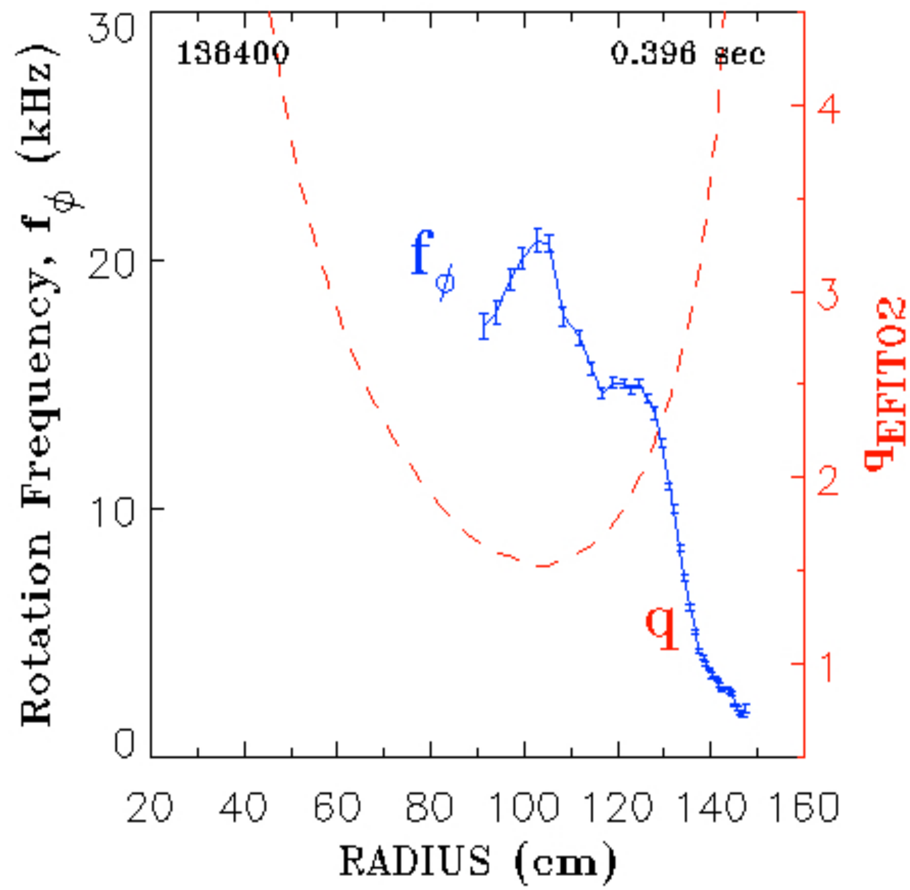
Shot 138400: Ip = 800 kA, Pb = 2MW

2.2 MW RF switched off at 0.394s

CHERS data with ***very small error bars***

Big island at R~122cm, f_Φ ~ 15 kHz ~ f_1





Doppler shift: $\omega' = \omega + \mathbf{k \cdot V} = \omega + k_\phi V_\phi = \omega + nV_\phi/R$

For tearing modes, $\omega << \omega' \sim nV_\phi/R$

Let $\delta B = \sum_{m,n} b_{mn} \exp[i(m\theta+n\phi)]$

If an island localized at $q=m/n$ has multiple toroidal mode numbers n,

then the island observed in the lab should have multiple harmonic frequencies with $f_n \sim n\, f_\phi$

Note: "~" means approx. equal because (a). $\omega/2\pi < 2$ kHz, and (b). 10% typical error bar on CHERS data

Resonance condition: $m/n=q$

Multiple n ⇔ multiple m

Large m => corrugated island surface/ *irregular boundary in Poincaré plot or **localized island with complex structure***

Most likely scenario in #138326: *Prf turned on* at 0.25s & form island @ q=1 enhanced transport *between 0.2817 - 0.2983s during MHO*

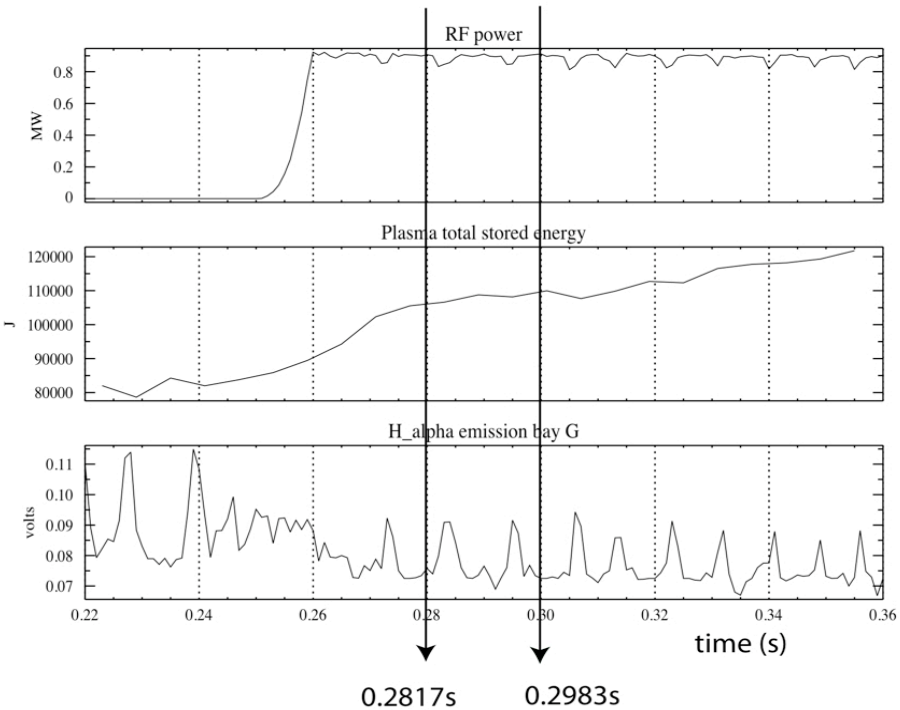
Pb=2 MW, 0.9 MW RF turned on at 0.25s, ELMy H-mode,

Wmhd rolls over after 0.27s ~ 8 ms before MHO appears in Mirnov spectrogram

- No sudden drop & *no broadband noise in Mirnov signal*

➔ NO sawtooth crash

- ***enhanced transport due to MHO*** – *a gentle way to vent excessive energy from plasma core*

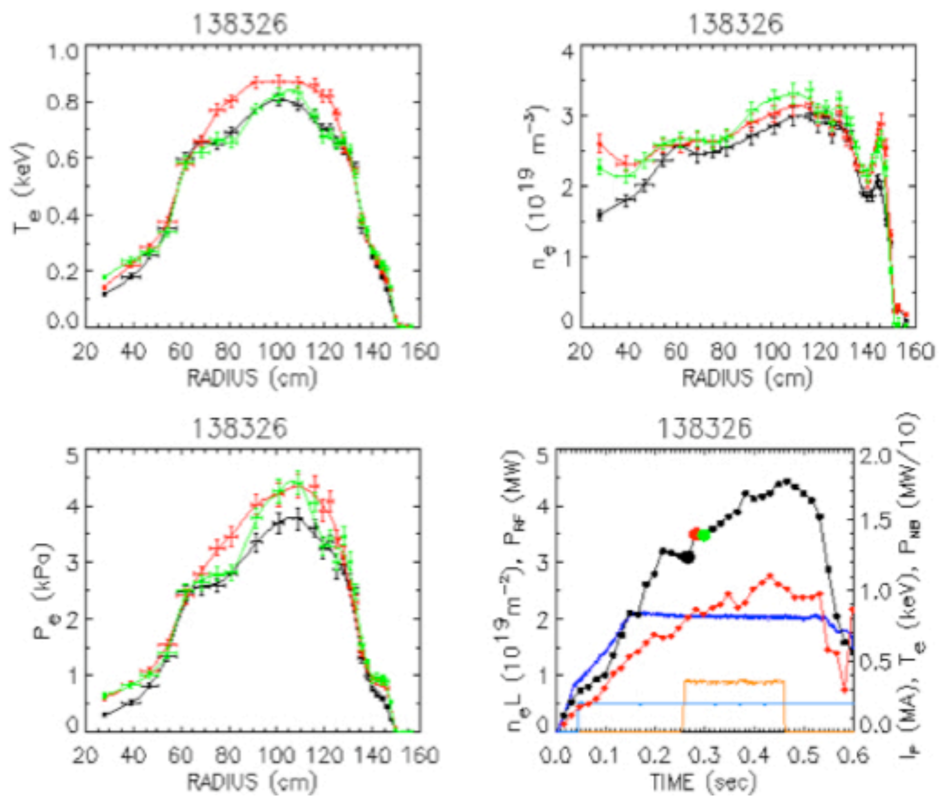


Te in plasma core drops between

0.2817 – 0.2983s

No Sawtooth crash

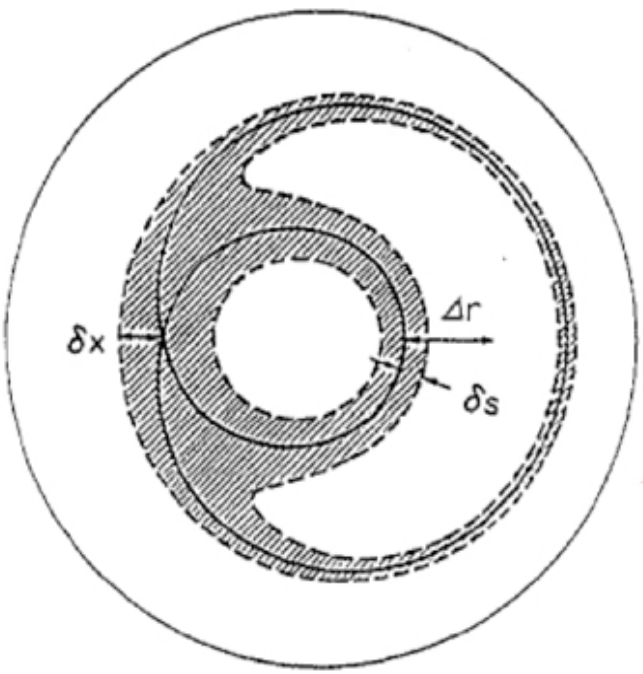
TS time: 0.2650s 0.2817s *(MHO)* 0.2983s



Stochastic magnetic field near separatrix of an island
➔ enhanced transport for electrons, ions and impurities

Stochastic B during sawtooth crash
- due to the overlap for second order island chains (action-angle variables)

Ref: *Lichtenberg et al., Nucl. Fusion (1992) for m/n=1/1.*



Express the perturbed B in Fourier series:

$$\delta B = \sum_{m,n} b_{mn} \exp[i(m\theta + n\phi)]$$

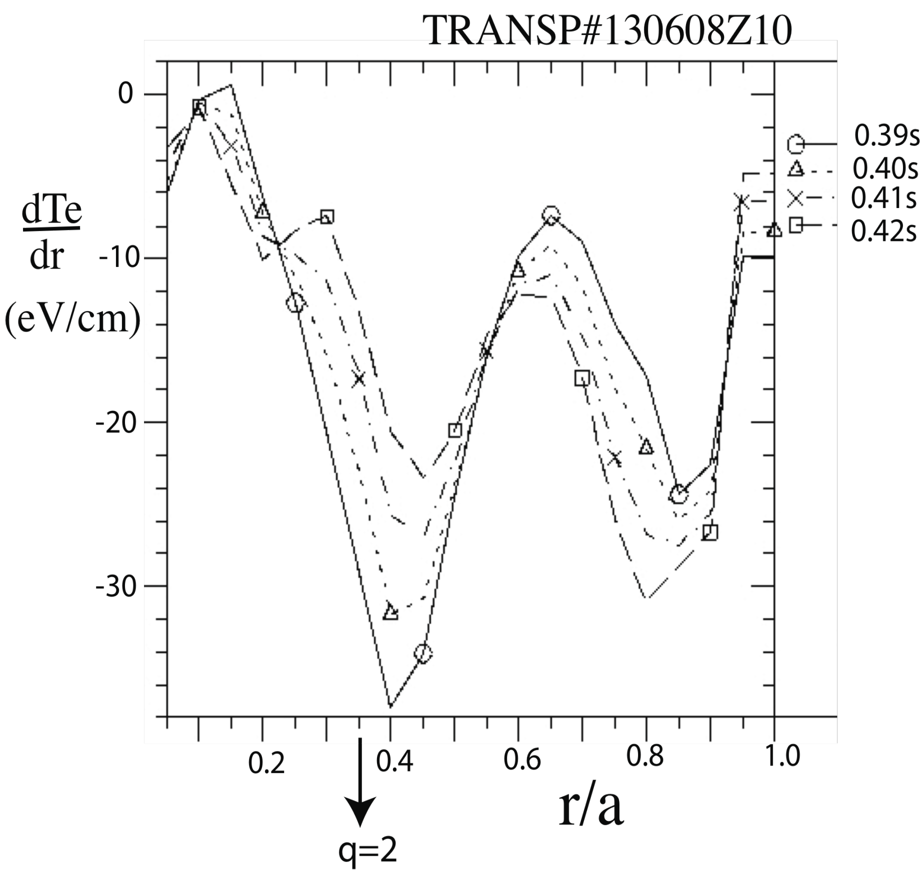
General property: *Any island with arbitrary n in a tokamak is surrounded by a separatrix, and there are stochastic B near the separatrix.*

When the island has many m, n harmonics, we can expect a *larger stochastic region for multiple stochastic layers :*

$$S = S_1 \cup S_2 \cup S_3 \ldots$$

⇔ *enhanced transport*

MHO near q=2 enhances electron energy transport



After MHO appears,

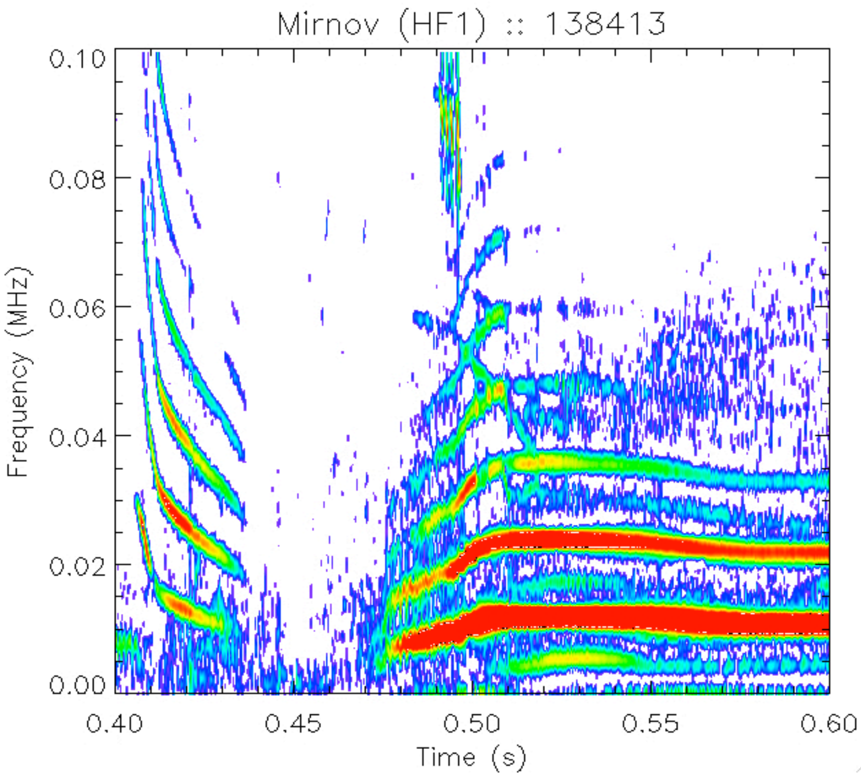
- Grad.Te decreases in plasma core (r/a < 0.6) ➔ *enhanced electron energy transport* there
- *Redistribution of energy*: the energy goes to r/a > 0.6 where grad.Te increases

MHO with rising freq after Prf switched off (#138143) Pb~2MW

*Island appears at edge & **ELMs suppressed – QH mode ?***

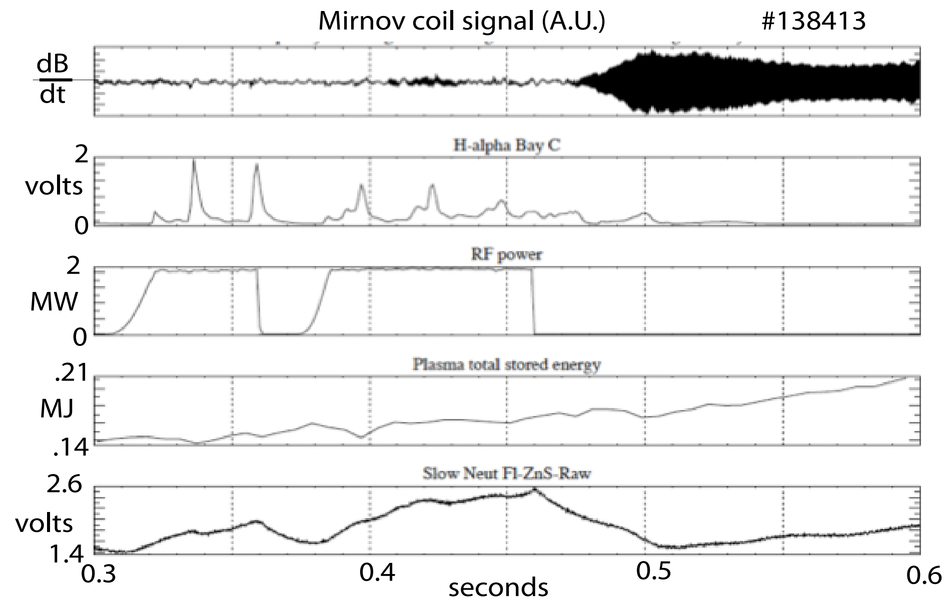
Ip=1MA, Pb=2MW, ne(0)<5.5e13cm-3.

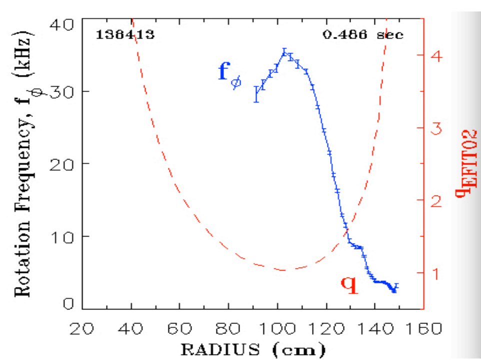
Prf turned off at 0.46s. An *island appears at R>130cm & grows in size and rotation speed.*

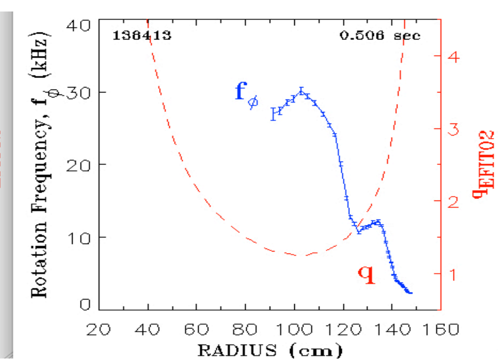


*Island at edge ⇔ MHOs & **suppress ELMs***

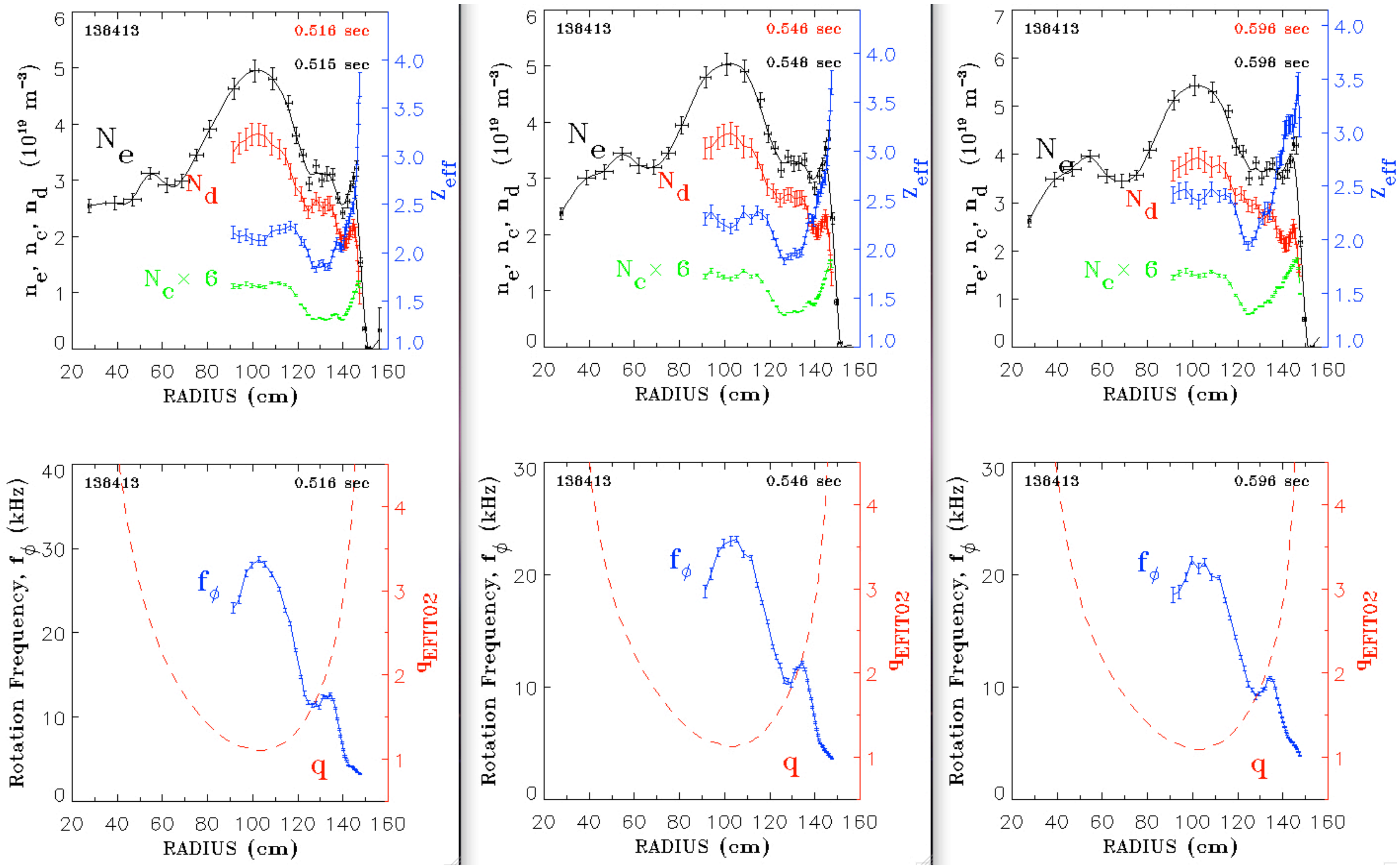
Wmhd & τ_E keeps rising beyond H-Mode level





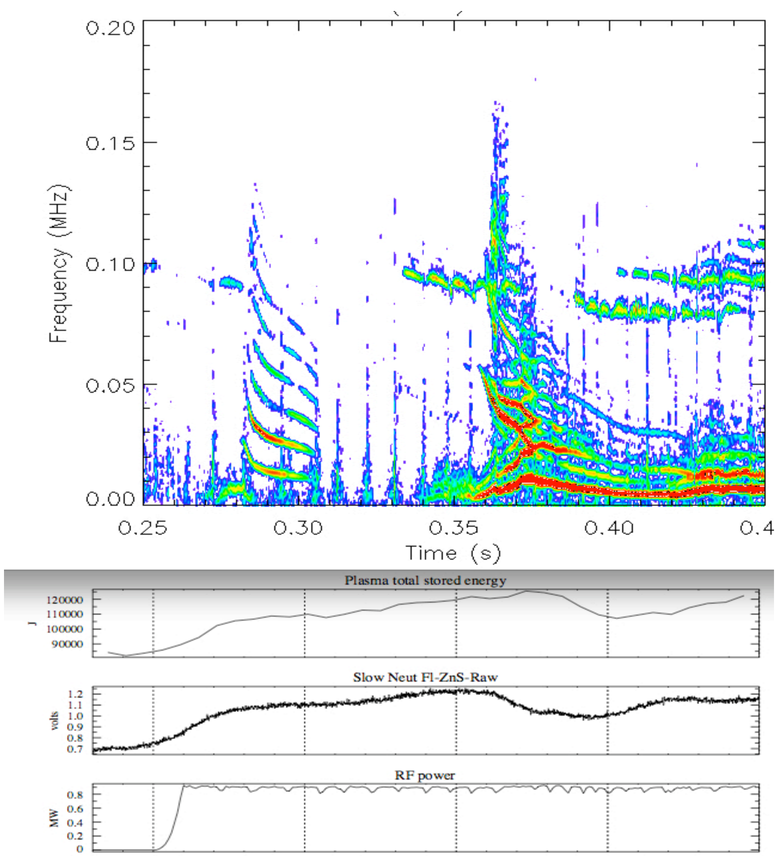


#138413: *Zeff(0) remains below 2.5* with edge island, *no ELMs*
ne(0) slightly higher (0.516 – 0.596s)

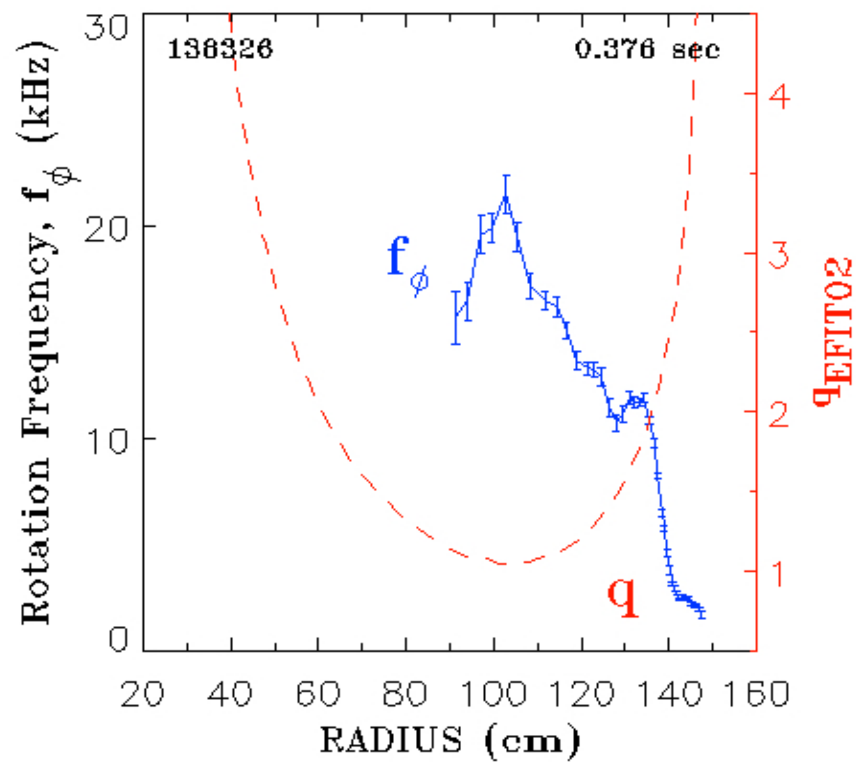


Avalanche: Combination of several sets of MHO at different regions

At 0.37s, *several sets of MHO* appear at the same time with different Δf : f_{ϕ} slowing down in plasma core & spinning up at plasma edge - *deterioration of momentum confinement*



Islands at different regions overlap ➔ **avalanche :** *severe deterioration of* ***global*** *plasma confinement* – 20% drop in neutron emission rate & 15% in stored energy with *fixed Pb+Prf*



MHO near edge (q~4) developed into locked mode

#129169: Ip=1MA, Pb=2MW, Prf=1.2MW, L-mode edge, RS before 0.27s

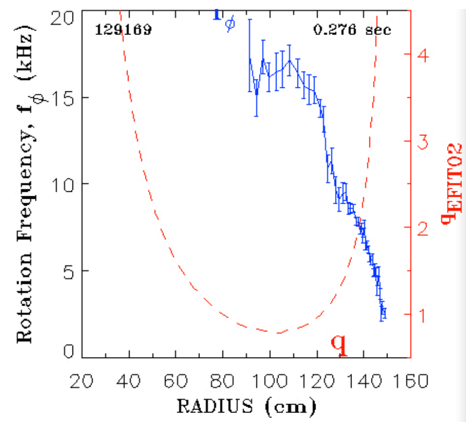
Rapid MHD growth at 0.27s,

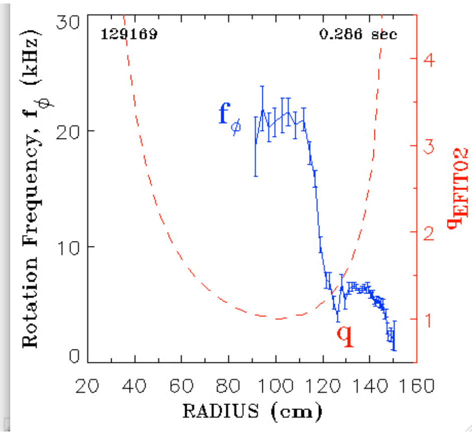
RF tripped off at 0.28s.

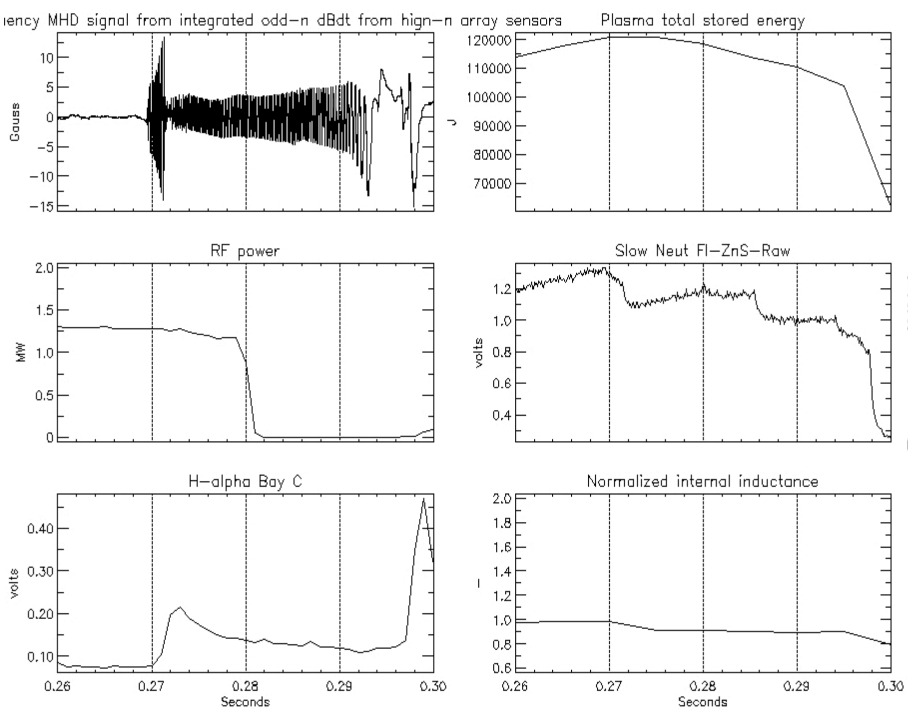
Large island at 0.286s, but not clear at

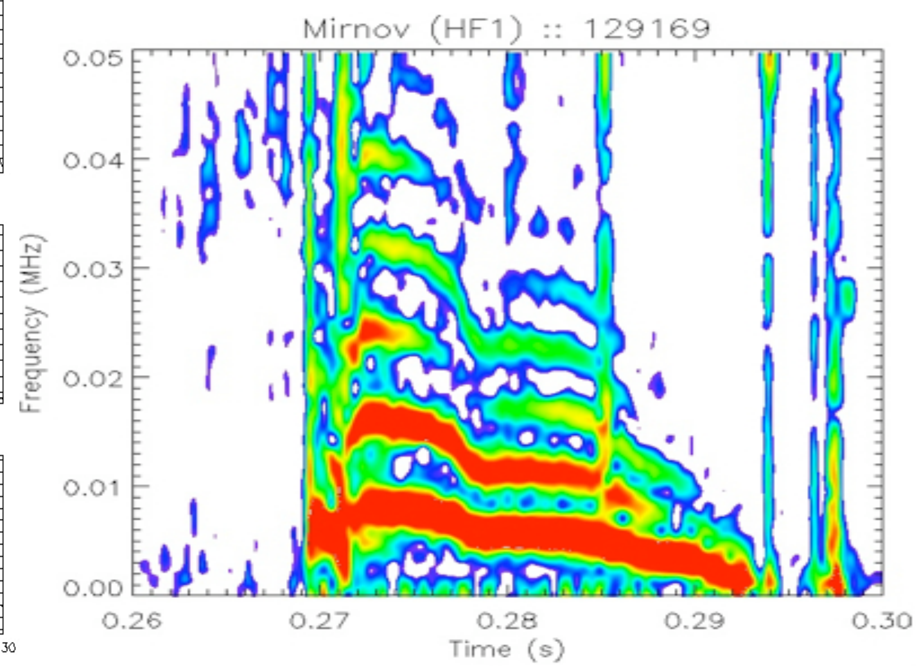
0.276s due to smearing effect

Locked mode (f ~ 0) at 0.293s





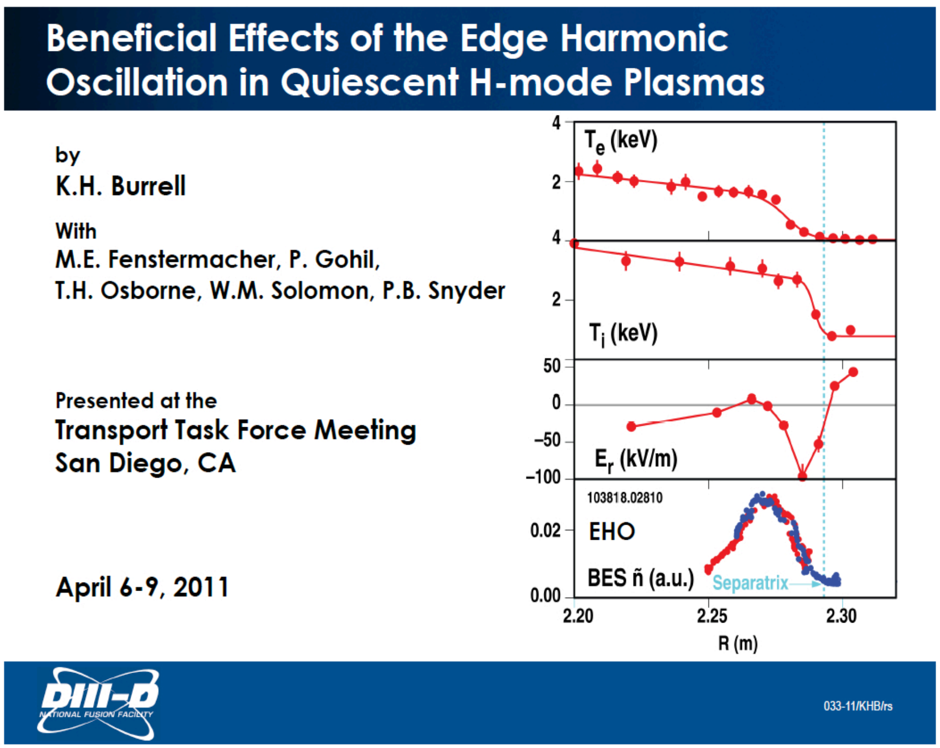




Relevance to conventional tokamak experiments

Quiescent H-mode in D3D

- ***edge*** *harmonic oscillations (**EHO**)*
- *Is it due to **island at plasma edge ?***
  1. *Ergodic B suppresses ELMs like RMP coils do*
  2. *Provides particle transport mechanism that peeling modes don't*



Current ribbon at q=4 in JET

- *Construct from appropriate values of b_{mn}*
- Island localized in θ & ϕ ⇔ multiple m, n

PRL **104,** 185003 (2010) PHYSICAL RE

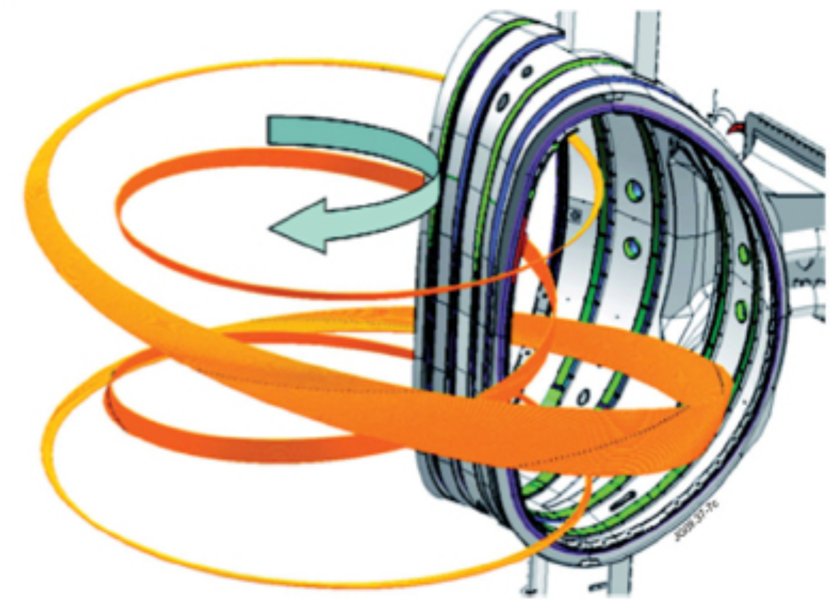


FIG. 4 (color). $q = 4$ spinning current ribbon that provides best fit to magnetic signals from Mirnov coil set, with 100–300 A.

Summary

MHOs are common in NSTX

- It can happen under many different plasma conditions.
- It is associated with a rotating magnetic island with complex structure - multiple helicity.
- The island location varies from core to edge.
- They can produce stochastic **B** and enhance plasma transport.
- Can cause multiple peaks in high-k scattering signal & in BES.

Is this a special feature of ST?

- *Not observed in core of conventional tokamaks.*
- *May be related to microtearing modes : can be unstable in NSTX from core to edge, but only at the edge in conventional tokamaks.*
- ***Speculations:*** *(a) EHOs in DIII-D QH-mode may be rotating complex islands at the plasma edge.*

  (b) The current ribbon in JET is an island with 100-300 Amp ; can be constructed with some values of b_{mn} .

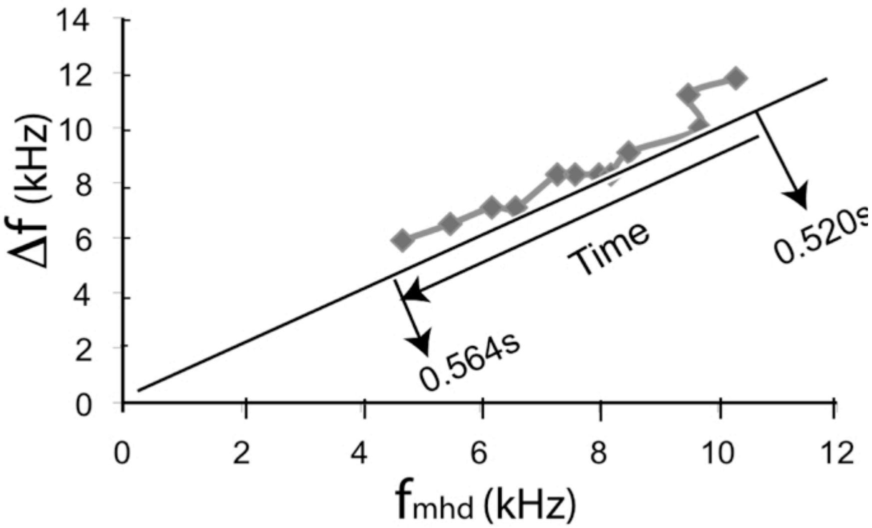
Back-up slides

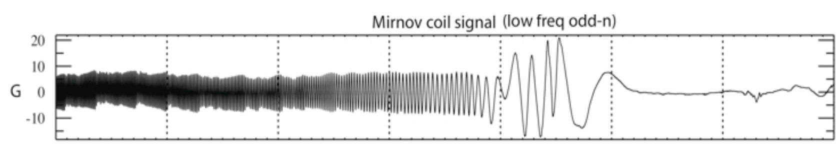
Back-up slides

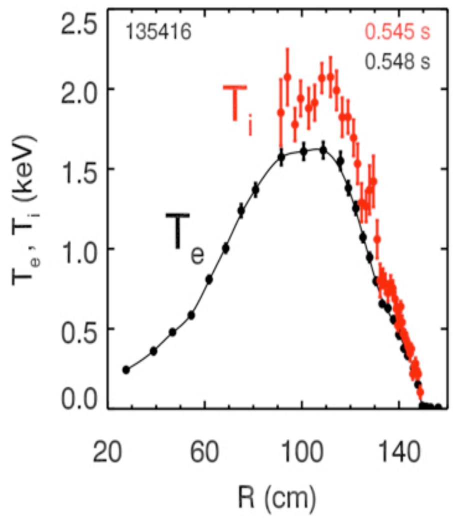
Plasma Response: *Multiple harmonics in high-k scattering & BES data*

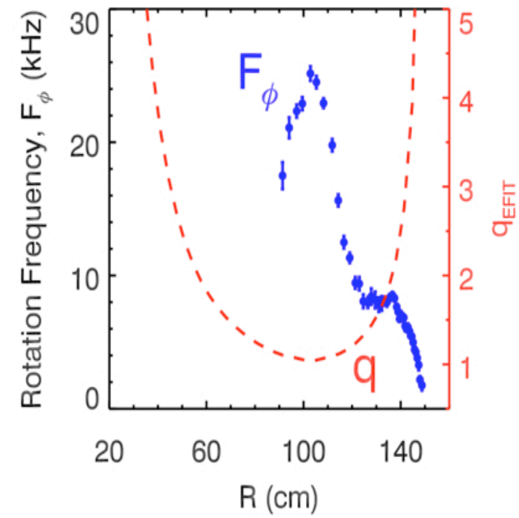
These data are rare : It requires a big island, and the scattering volume must be at the right place

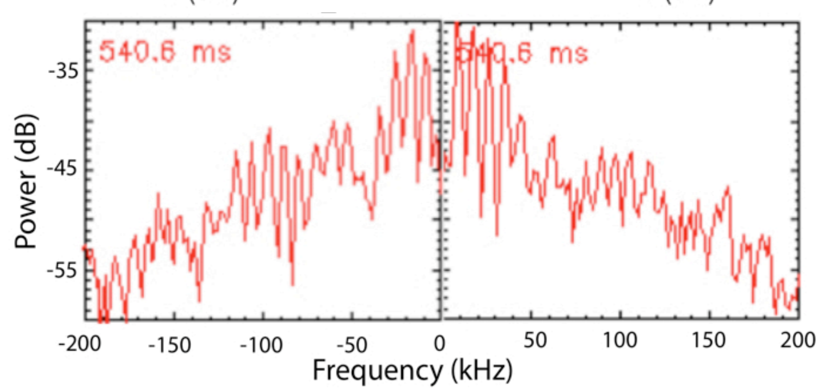
nth harmonic of island rotating at $\mathbf{f_\phi}$ produces EM fields in plasma with $\mathbf{f_n = n\, f_\phi}$ and the plasma will respond at the same freq $f_n = n\, f_\phi$: ***Oscillations need not be normal mode - D(ω,k)~0***





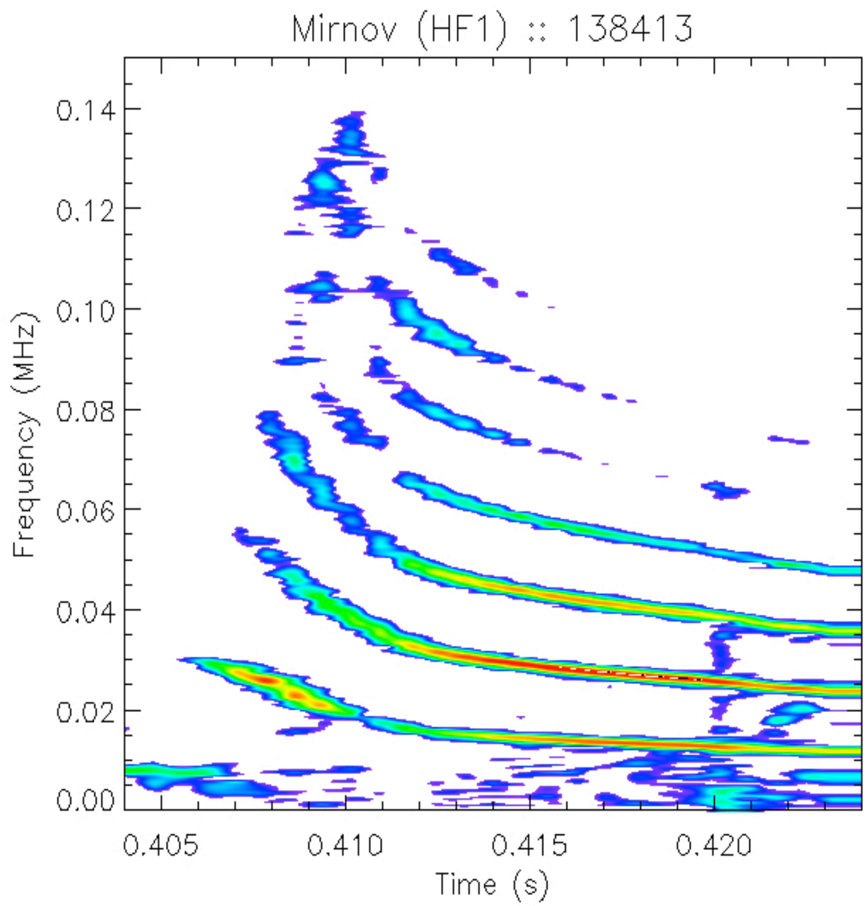




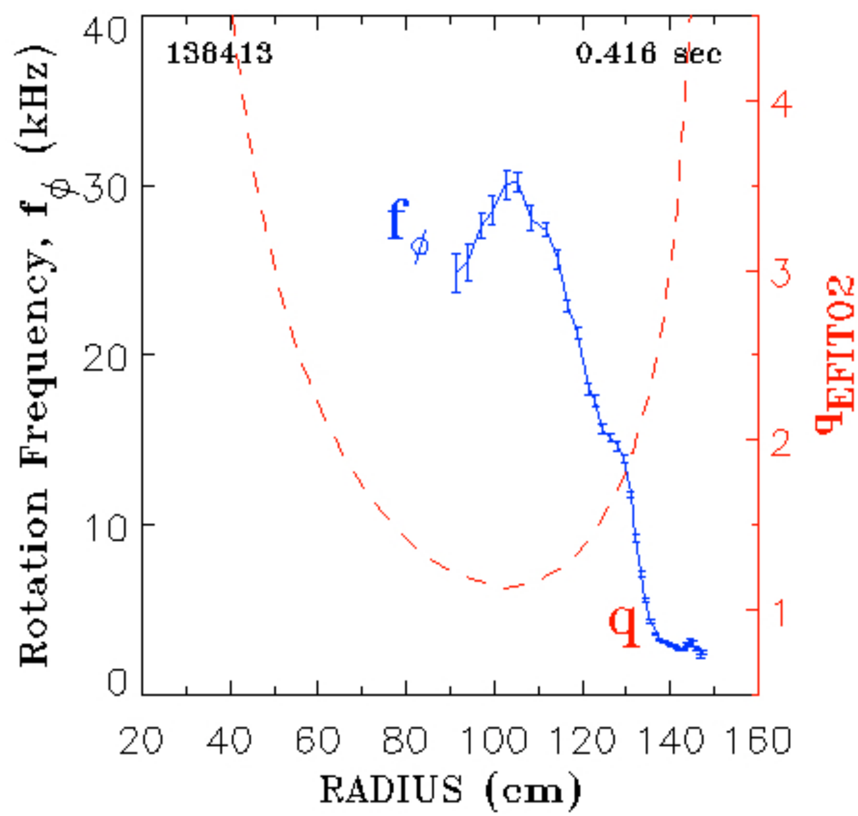


Need high quality CHERS data to see small islands

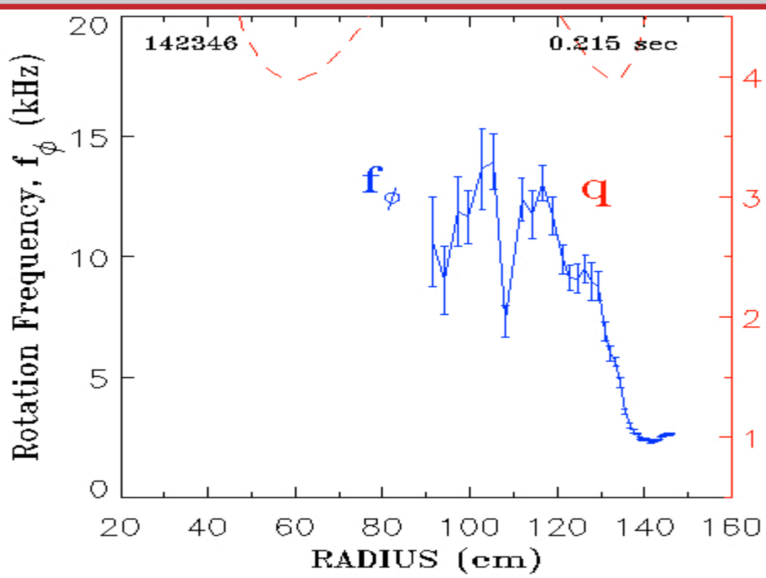
Small island usually has more freq peaks & short life time

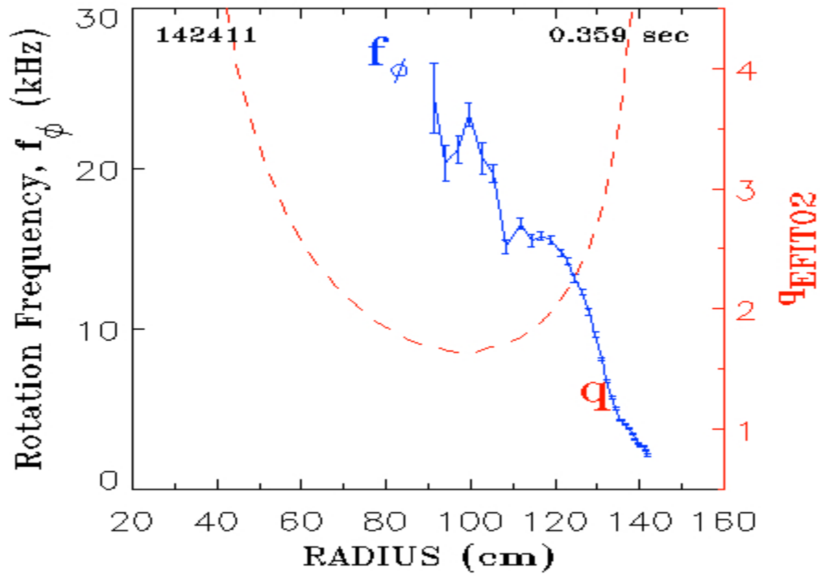


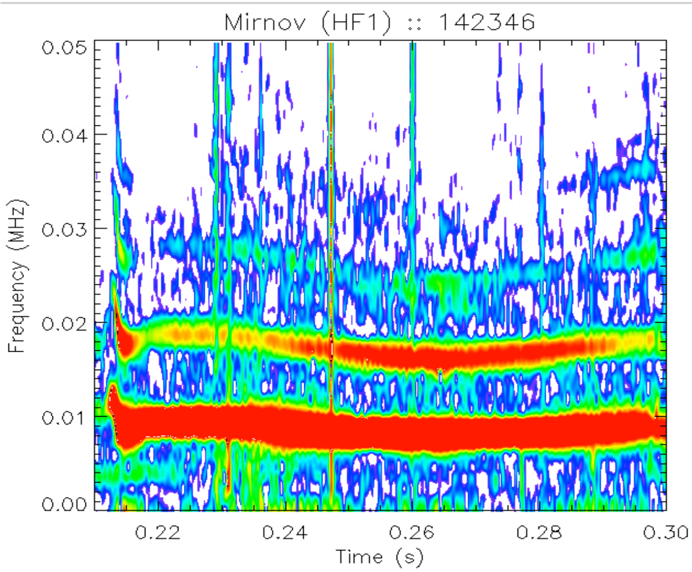
Small island only observable in high quality CHERS data – *need small error bars*

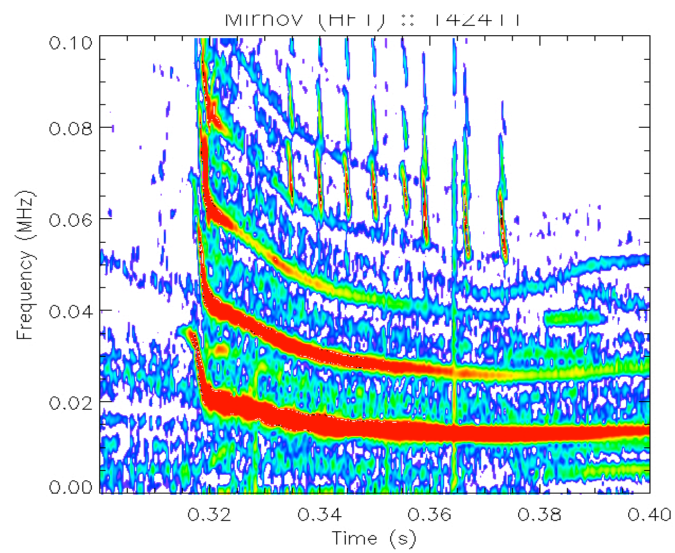


Shots with bigger islands: #142346: Pb~6MW
No RF for both shots - #142411: Pb~3MW

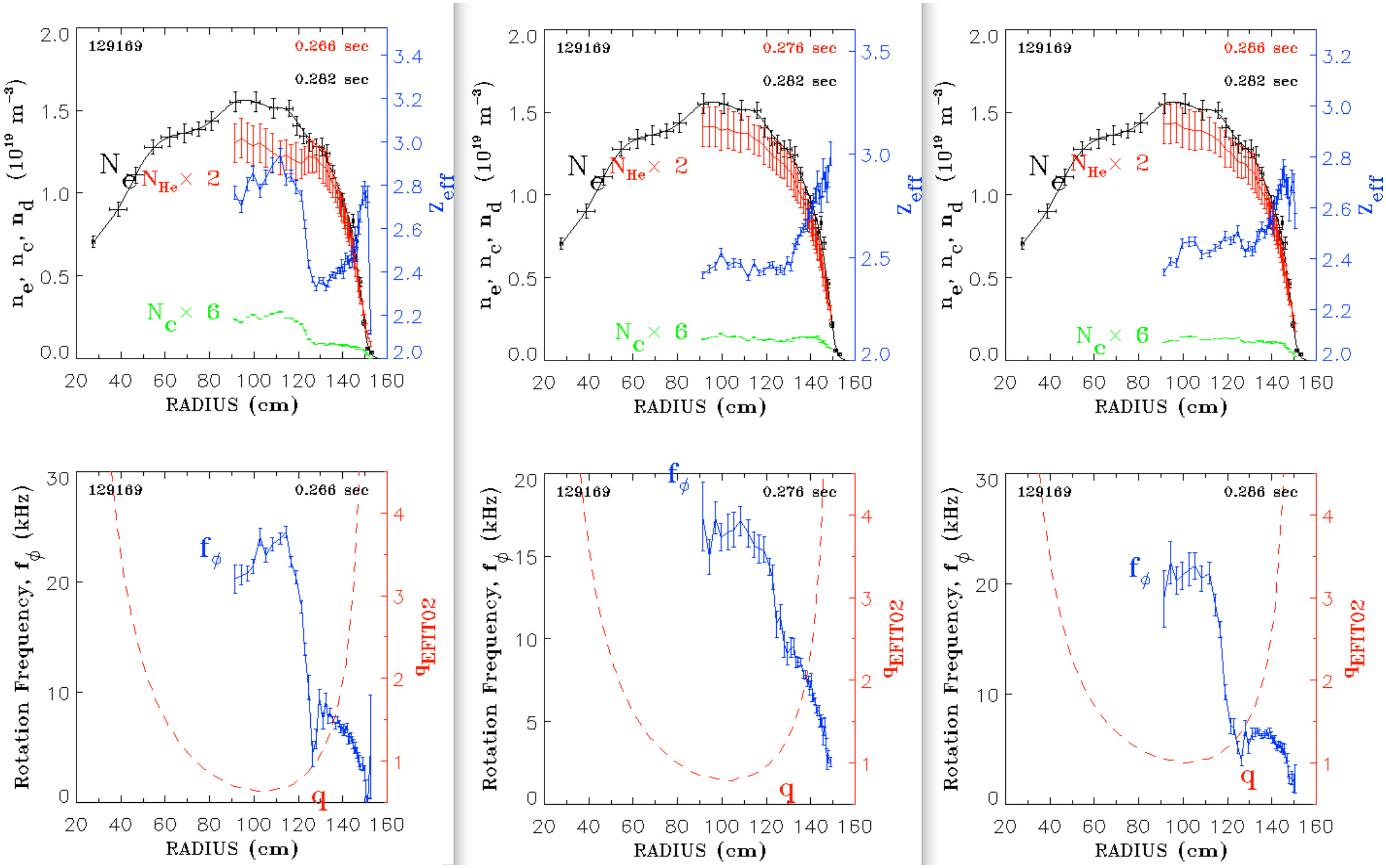








Zeff(0) dropped rapidly after q(0) fell from 3.2 to 1.3 (high RS before 0.27s)
& slightly reduced after edge island formed (#129169)



Impurity accumulation without ELMs

***RMP** was applied **to trigger ELMs** and reduce impurities in plasma*

Nucl. Fusion **50** (2010) 034012 J.M. Canik *et al*

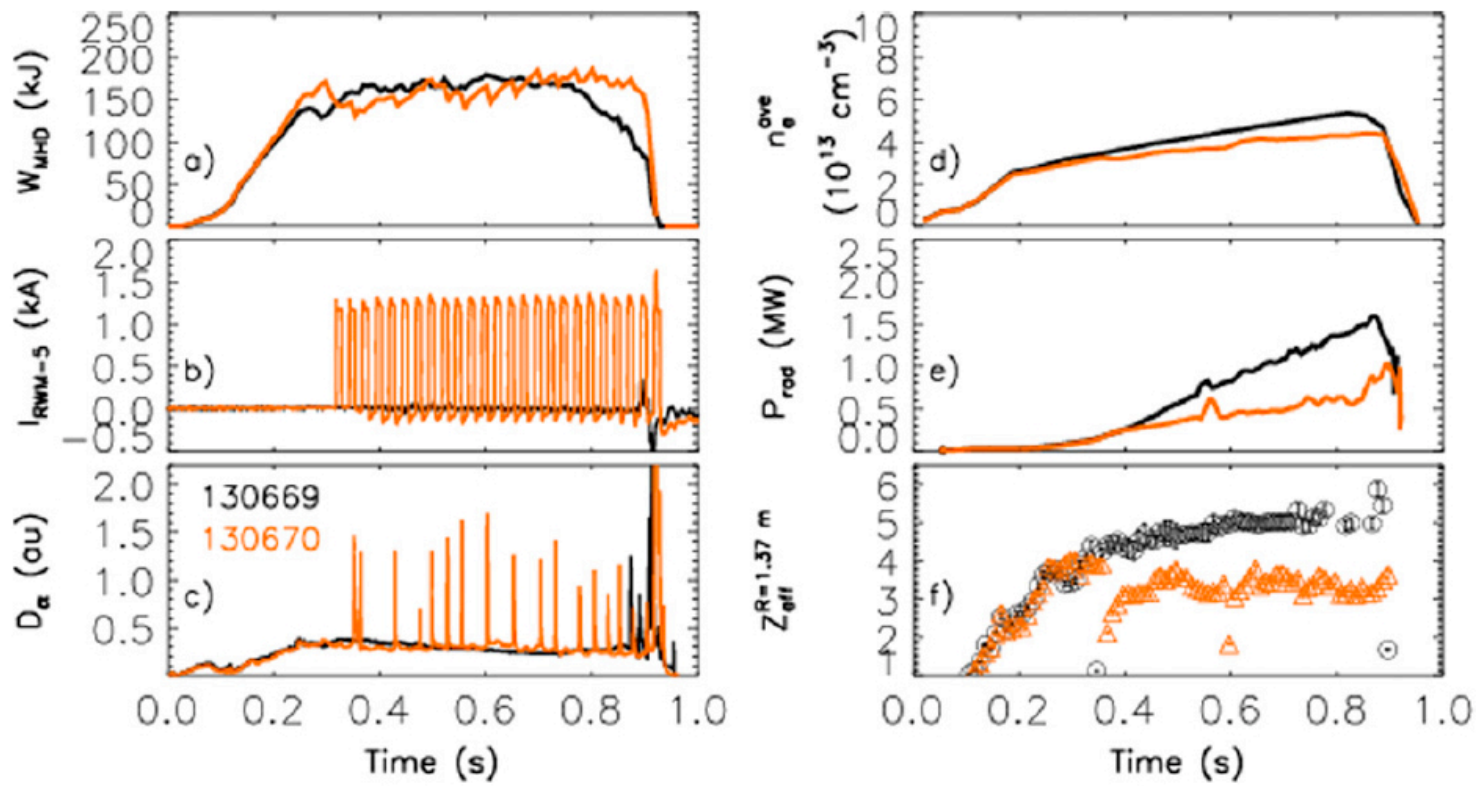


Figure 6. Time traces of (*a*) stored energy, (*b*) current in the perturbation coil set, (*c*) D_α emission, (*d*) line-averaged density, (*e*) radiated power and (*f*) effective charge based on carbon density at $R = 1.37$ m (near the top of the pedestal) for a control discharge (black) and with pulses of RMP applied (pale solid lines).